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Aligning Integrated Assessment Modelling with Socio-Technical Transition insights: an application to low-carbon energy scenario analysis in Europe

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Abstract

In this study, we present and apply an interdisciplinary approach that systematically draws qualitative insights from socio-technical transition studies to develop new quantitative scenarios for integrated assessment modelling. The approach allows to focus on the role of actors in meeting the European Unions' 80% greenhouse gas emission reduction objective for 2050. We identify the transition narrative as an analytical bridge between socio-technical transition studies and integrated assessment modelling. Two fundamentally different transition narratives are distinguished. The first transition narrative outlines how large-scale innovation trajectories are driven by incumbent actors, whereas the second transition narrative assumes more 'alternative' options enacted by new entrants with strong opposition to large-scale technologies. Based on the multi-level perspective, a typology has been created on the actors and momentum of change for several technological and social niche-innovations. This typology is used to develop new quantitative scenarios for integrated assessment modelling. Although both developed transition pathways align with the European Union's low-carbon objective for 2050, we find that each pathway depicts a substantial departure from systems that are known to date. Future research could focus on further systematic (joint) development of operational links between the two analytical approaches, as well as work on improved representation of demand-oriented solutions in techno-economic modelling.

Keywords

Interdisciplinary, MLP, integrated assessment, IAM, socio-technical transitions

1 Introduction

Transitions towards a low-carbon society depend on the progression of a wide variety of different factors and processes. Integrated Assessment Models (IAMs) are computer-based instruments that are commonly used to analytically support our understanding of long-term transitions, global climate change and the various complex interlinkages between human and natural subsystems. As IAMs have a comprehensive representation of the global system, they are commonly used to evaluate the implications of different policy decisions on both the human and natural system over time. However, the main drawback is that these instruments can only focus on those elements that can be captured in mathematical formulations. As IAMs are generally powered on (energy) engineering principles and neo-classical economics, they generally assume that system transitions are driven by cost-effectiveness and technological substitution decisions alone.

This techno-economic focus has led to a discussion amongst scholars on the interpretation of IAM scenario results (see e.g. Anderson and Peters (2016); Fuss et al. (2014); Kruger (2016)), especially as scenarios may present outcomes that could be controversial in the light of other criteria such as risk and societal support. For instance, researchers have pointed at the large-scale deployment of bioenergy and CO_2 capture and storage systems (creating so-called ‘negative emissions’, a geoengineering strategy to reverse damaging impacts from rising GHG emission levels) in most of the low-carbon transition depictions in the *5th Assessment Report* (AR5) by the United Nations’ *Intergovernmental Panel on Climate Change* (IPCC) (Clarke et al., 2014). These low-carbon transition scenarios thus convey an unanimous message that future societies will become dependent on unprecedented levels of human intervention, which raised questions among scholars about (1) the assumptions on the availability of these technologies and (2) the level of political (un)willingness accounted for in these modelled processes (Anderson and Peters, 2016; Geden, 2015; Peters, 2016). As IAMs do not account in much depth for various institutional, political, social, entrepreneurial and cultural factors, the ex-ante assessments could be considered as offering narrow technology-oriented perspectives on transitions towards a low-carbon society. In response to this caveat, various scholars have called for broader interdisciplinary research aimed at introducing greater realism into IAM scenarios (e.g. Kruger (2016); Peters (2016); Stern (2016); Victor (2015)).

Earlier work has attempted to move beyond the techno-economic focus in integrated assessment modelling and implement more realism into the integrated assessment frameworks. Various methodological approaches have been developed and applied throughout time, such as, for example:

1) Using qualitative and comprehensive storylines to outline the considered socio-political development over time (e.g. as found in the Special Report on Emission Scenarios (SRES) or Shared Socioeconomic Pathways (SSP) (Nakicenovic et al., 2000; O’Neill et al., 2014)). Storylines are implemented via the use of broader rule-sets in IAMs, which allow to emulate real-world processes to a greater extent (such as the inclusion of limitations in joint international commitments and restricted availability of energy technologies, see e.g. Clarke et al. (2009); Kriegler et al. (2013); Kriegler et al. (2014));
2) Devising participatory processes with stakeholders to incorporate qualitative elements in model-based scenarios on future change (Salter et al., 2010; Van Asselt et al., 2003). Several methods are distinguished in literature to include a broader context of value in IAMs, such as *participatory modelling*, *facilitated modelling* and *interface-driven modelling* (Salter et al., 2010), which describe the various modes in which participatory groups can contribute. Schmid and Knopf (2012) have, for example, applied a participatory modelling approach in which stakeholders are involved in model-based analyses via an iterative process of dialogues. Alternatively, the United Kingdom has engaged public stakeholders via the ‘*My2050’* serious

game interface[1], which allowed broader learning about future transition routes and are considered more publicly accepted (Comber and Sheikh, 2011);

3) Making social systems more explicit or internally dynamic in IAM modelling. As IAMs are rooted in neo-classical economics, most assessment studies deploy a single rational agent makes decisions based on cost-effectiveness considerations (De Cian et al., this issue). This singular view on decision making is acknowledged to not reflect the multi-dimensionality and complexity in social systems (Geels et al., 2017; Rotmans, 2006). To account for social systems in IAMs, model developments have focussed on expanding the single actor representation to a wider range of "consumer groups", which has gained some substance within transport modelling (see e.g. McCollum et al. (2016)). Alternatively, the impacts of diverging social actor behaviours on a low-carbon transition have also been studied via stochastic modelling approaches that emulate numerous single actors and their preferences (Li, 2017).

Although these methodological approaches allow greater realism into the models' architecture, they all contain limitations. For example, detailed qualitative storylines are considered to be oversimplified and static characterisations of political, institutional and social change and can therefore offer only limited analytical support for planning future energy transitions. Moreover, although a broader representation of actors (real or virtual) allows the adoption of more diverse strategies in integrated assessment modelling, the responses remain motivated by the techno-economic principles in the model. IAM scenario analysis on low-carbon transitions may thus (1) expose a dominant focus on materialised change without taking note of the instigators and incubators driving the change and therefore (2) reason on current power relations and user practices in society without allowing other forms of governance and development.

Given the importance of social systems in accelerating or delaying transition processes, it is of interest to better reflect and study their influence on low-carbon transition strategies over time. In this study we therefore attempt to combine computer-based interpretations of systems change with insights of socio-technical transition studies. The study is framed around the European Unions' long-term objective of lowering total domestic greenhouse gas (GHG) emissions by 80% in 2050 compared 1990 levels. In the next section we first elaborate on the two analytical approaches used to combine techno-economic and socio-technical assessment in a single study. Section 2 elaborates on the identification and operationalisation of shared concepts. Section 3 presents the scenario results in terms of energy supply and demand. Section 4 discusses the applied methods and Section 5 summarises and concludes.

2 Towards an interdisciplinary analytical framework and its operationalisation

2.1 Selection of analytical approaches

In this study, we combine two analytical approaches that offer different but complementary views on the evolution of low-carbon transitions.

[1] http://my2050.decc.gov.uk/

The first analytical approach considers the evolution of low-carbon transitions through the techno-economic lens used in computer-based modelling. A wide variety of computer-based interpretations on low-carbon transitions exist to date, which have been developed by (1) economic models, (2) energy system models or (3) integrated assessment models. Differences in interpretation are a result of differences in sectoral, technological, spatial and temporal detail (see e.g. Hourcade et al. (2006); Jebaraj and Iniyan (2006); Kriegler et al. (2015)). Here, we predominantly focus on the TIMER model (van Vuuren, 2007), an energy system simulation model representing simplified economy-environment causal chains, which is nested in a broader framework on global systems change (IMAGE) (Stehfest et al., 2014). Combined, the TIMER/IMAGE model is able to reflect year-to-year investment decisions and the implications to society based on specific rules about investment behaviour, fuel consumption, technological learning and diffusion patterns (van Vuuren, 2007). As recent model developments have led to more explicit representations of sectors and actors (see e.g. Daioglou et al. (2014); de Boer and van Vuuren (2016); Girod et al. (2012); Isaac and Van Vuuren (2009)), the TIMER/IMAGE model provides opportunity to address social actor behaviour in more detail within the broader scope of global system change modelling.

The second analytical approach considers the evolution of low-carbon transitions through diverse socio-technical developments. A variety of theoretic frameworks has emerged in the last few decades that provide insights into social actor behaviour in, and the governance of, low-carbon transitions (see for an overview e.g. Markard et al. (2012)). The Multi-Level Perspective (MLP), as one of these theoretic frameworks, is a widely used analytical framework to study transitions (Geels, 2002; Geels and Schot, 2007). The MLP recognises that transitions are non-linear processes resulting from multiple endogenous and exogenous developments at three different analytical levels: the niche, regime and landscape level. For this study we have selected the MLP as it is a fairly established perspective within transitions studies and has (1) explicit consideration of the time dimension (linking future goals to near-term decisions), (2) relative narrative simplicity (e.g. struggle between niches and regimes in the context of slow-moving landscapes), (3) specification of systemic processes and underlying mechanisms, (4) explicit linkage of actors and material systems, and (5) is partly supported by similar historical insights as the model-based assessments.

Although the analytical approaches are acknowledged to be fundamentally different, several elements can be recognised that are in close proximity to each other which provides a promising starting point for further interaction. Given the differences in (1) assessment style (e.g. narrative-based vs. quantitative assessment), (2) analytical focus (e.g. emergent and disorderly developments vs. stylised trends that are extended into the future) as well as (3) the type of metric used to describe transitions (qualitative vs. quantitative descriptions of change), no full integration of both analytical approaches is pursued (Geels et al., 2016). We nonetheless agree with Turnheim et al. (2015) that '*there are good grounds for a common framing of analytical and governance problems [to] be addressed by combining different lenses and styles of explanation*" and describe a method for a softer integration of both transition conceptualisations in the following sections.

2.2 Defining shared concepts

A softer integration of IAM and MLP requires the identification of common concepts. In the formulation of both disciplinary philosophies we can detect several concepts that are considered key for both analytical approaches. These shared concepts provide some leeway for conceptual interaction. The following sections elaborate on these shared concepts.

2.2.1 Niche momentum and system inertia

A shared concept between the analytical approaches can be found in the way how systemic change is interpreted. Although differences exist in the semantics and connotations, we find that both analytical approaches apply the concepts of *niche momentum* (departure from the status-quo) and *system inertia* (stability and robustness of a regime to maintain itself) to explain systemic change. For example:

1) MLP applies the concepts of momentum and inertia to describe the success or failure of interactions between actors and social groups, which help to explain how systemic change has materialised and what the ramifications are to the existing regime. The analytical emphasis of MLP is on qualitative elements, such as power struggles, emergence of networks and coalitions, and the co-evolution of change processes across multiple dimensions (e.g. social, technical, economic, political or cultural dimensions).

2) IAMs apply the concepts of momentum and system inertia to indicate the rate of change over time. As IAMs lean on more abstract generalized patterns of change, e.g. using learning and logistic growth curves to endogenously represent the evolution of technological growth and diffusion, they offer a more narrow perspective on systemic change.

2.2.2 Transition narratives

Another shared concept is recognised in the effort to classify the course of systemic change in a so-called "transition narrative". Both analytical approaches devise (transition) narratives as a pragmatic research instrument to describe change, though each with a different purpose:

1) The MLP perspective provides narrative *explanations* by focusing on the interactions between niches, regimes and landscapes. Given the rather intangible and fluid nature of many of the concepts addressed in MLP, the narrative approach offers the opportunity to codify and detect "generic" patterns that result from interactions between actors (e.g. groups making moves, taking actions and react to each other) (Geels and Schot, 2007).

2) For IAMs, the narrative or storyline approach is generally used to create a context around the quantitative mathematical formulations. Given how social systems find no direct analogue in IAMs, as they are implicitly encapsulated in the 'hard' technological and aggregated system processes and mathematical formulations (see also De Cian et al. (this issue)), scenario narratives provide the opportunity to impose alternative sets of assumptions to the models' default configuration.

2.2.3 From shared concepts to conceptual interaction

In recognising and defining the shared concepts, it becomes clear that MLP embodies a wealth of information on the driving elements of socio-technical transitions, which is collected in a transition narrative to create a vast corpus of explanation on systemic change. Alternatively, IAMs contain a wealth of information on causal (techno-economic) interrelationships, which require corrective input to provide a (new) sequence of change over time. Conceptual interaction may therefore take the form of MLP informing IAMs with bottom-up insights on recent and emerging developments for a wide range of niche-innovations, with explicit distinction of the actors in charge of these developments.

To remain compatible with and comprehensible to both analytical approaches[2], we identify two archetypical transition narratives that can function as an analytical bridge between both scientific approaches (drawn from Geels and Schot (2007)):

1) The first narrative (*Technological Substitution*) describes how stabilised niche-innovations are awaiting a window of opportunity to gain bigger market shares. This window of opportunity is described as a "specific shock" that initiates socio-technical change. The narrative represents a portfolio shift by regime actors, who are focussed on replacing existing socio-technical elements with versions that better fit with the new environment. Other elements (e.g. user practices, lifestyles, governance arrangements) remain close to the existing regime.

2) The second narrative (*Broader Regime Change*) describes a lack of faith in existing regimes to respond appropriately to the new environment. It entails a shift to a new socio-technical system, based on the breakthrough of radical niche-innovations that entail not only technical changes but also wider behavioural and cultural changes and new user practices and institutions.

Both analytical approaches benefit from identifying niche-innovations as part of either one of these narratives. For MLP it allows to provide a frame to which real-world developments can be structured (via recurrent patterns and deviations), whereas IAMs can devise these transition narratives to distinguish between two different types of actors that drive systems change (namely (1) incumbent actors that are seeking a new balance within an existing regime, or (2) new actors that are destabilising the existing regime and replacing it with something new).

Together the analytical approaches are found to share conceptual space in (1) the run-up towards the present situation (with MLP "input" oriented and IAM "outcome" oriented) and (2) the interpretation of how systems will evolve over time (with MLP encompassing knowledge of the build-up and tendency of niche-innovations to challenge the existing regime, while IAMs depict the course of development for niche-innovations under a changing landscape over time (see Figure 1 for an illustrative example).

[FIGURE 1 HERE]

Figure 1 - Illustration of the two considered analytical approaches and their shared conceptual space. The arrows represent the various niche developments that can be studied with MLP. The lines represent the stylised conceptualisation of system change based on historical "outcome" data (dashed) and the interpretation of the IAM on how it extends into the future (solid). Δt represents the considered timespan for study in MLP, of which is assumed that the current orientation of niches can be projected into the future. The red and blue lines represent the outcome of conceptual interaction, in which MLP can provide insight on (1) niche momentum (as represented in the slope of the line) and (2) the strategic actor driving a niche-innovation (as represented in the colour of the line). This information allows IAM analysis to adopt more forward-looking perspectives into projections, while accounting for specific actor bases.

[2] Recognising here that conceptual interaction needs (1) a level of simplicity (stylised but representative), (2) take note of both bottom-up developments as well as top-down (landscape or system-wide) pressures over longer periods of time (which allow a departure from the existing system) and (3) to pay specific attention to agents of change (given the lack of representation of social actor groups in IAMs).

2.3 Operationalising the interaction

2.3.1 Drawing insights from shared concepts

Conceptual interaction between the two analytical approaches can be operationalised by drawing insights from case-studies looking into social and technological niche-innovations and using the information in quantitative modelling. In a first step, we have accumulated the findings of multiple case-studies to create a typology on systemic change. The case-studies have been selectively drawn from (1) exemplar countries in Europe (Germany, the Netherlands, United Kingdom and Sweden) and (2) three important economic domains (power, mobility, and heating). On average about 6-7 green niche-innovations have been selected per domain in each country for further study (see supplementary information table A1 for an overview).

The niche-innovations have been analysed across three analytical dimensions, which look into the (1) innovation and market trajectories (techno-economic assessment), (2) actors and social networks (socio-cognitive assessment), and (3) the governance and policies over the last 10-15 years. The assessment as a whole allowed to draw an overall qualitative judgement of the current momentum of each niche-innovation, which is assumed to provide some indication of the potential towards the near future. Niche momentum could be judged as having “very low” (inert system) or “very high” (breakthrough) momentum with three intermediate values in between. In a similar fashion, the MLP assessment also provided insights into the subset of actors driving the change for niche-innovations by categorising the case-studies into either of the two transition narratives (respectively *Technology substitution* or *Broader Regime Change*).

The outcomes of the MLP assessments are visualised in Figure 2. The typology reveals that the various countries and domains are at varying stages of an energy transition. The electricity domains throughout Europe expose developments with medium to high momentum, signalling that a transition is eminent for these niche-innovations. Niches in the mobility domain are mostly ranked as having medium to low momentum, signalling that a departure from the established system is in a much earlier phase. Niches in the heating domain, however, depict low to very low momentum, suggesting an inert system that is not likely to adopt any new practices soon. In general, the figure shows that technological innovations are currently advancing more than most social innovations, for which momentum is low. Interestingly, the niche-innovations appear to not uniformly classify into a certain transition narrative, implying that different motivations are driving niche-innovation developments in different countries (for example, the development of onshore wind power has been mostly driven by incumbent actors in the UK, whereas the same niche was mostly adopted by new actors in Germany).

We apply equal weighing[3] of the case-study findings to derive an overall momentum of change and deduct which actors are most likely involved in driving the change (represented by the bars in Figure 2). This reveals to what extent niche-innovations (1) are likely to gain momentum and (2) are

[3] One may argue whether equal weighing of the driving forces is an appropriate measure to trace out the course of change for a region as a whole. However, given how each represented EU Member State is (1) exemplar in the field of technological innovation, (2) bound to the same European GHG emission reduction target of 80% in 2050 compared to 1990 levels and (3) together represent a large share of emissions within Europe (representing ~40% of total European GHG emissions over the last 20 years), the collective action among these regions can be considered characteristic of the overall low-carbon transition strategy within the European context.

developed by a specific set of actors driving the change. Ambiguous outcomes underline an important caveat in our approach, as currently we only draw information on emergent processes of change with a very prominent classification. Although we acknowledge that multiple interpretations are possible for the type of actor taking the lead, we leave a more pluralistic approach to future work. In the following section we elaborate on how these detectable patterns from MLP analysis have been used to develop IAM scenarios.

[FIGURE 2 HERE]

Figure 2 - Overview of niche momentum and actor per country (triangle) and the overall deducted patterns (bars). Electricity: DE (Rogge et al., 2015) UK (Geels et al., 2015)**. Mobility:** NL (Turnheim et al., 2014) UK (Hodson et al., 2014). **Heating:** DE (Thema et al., 2014) UK (Turnheim and Berkhout, 2014) SWE (Nykvist and Dzebo, 2015). Abbreviations BEV: Battery Electric Vehicle. PHEV: Plug-in Hybrid Electric Vehicle. H2: Hydrogen fuelled vehicle.

2.3.2 Translating MLP insights into IAM analysis

To study the influence of actors and actor behaviour on low-carbon transition strategies, we devise the TIMER/IMAGE integrated assessment model to consistently test the course of development over the 2010-2050 time horizon. This requires a translation of the rich qualitative information as provided in the MLP studies to applicable input for the TIMER/IMAGE model.

- To distinguish between specific actors driving change, we have used the typology of Figure 2 as a guide to promote or weaken the representation of a niche-innovation in the respective scenario – as a unanimous allocation of a niche-innovation to either one of the transition narratives provides confidence that a transition is driven by a specific strategic group of actors.
- Regarding the representation of "niche momentum" in the model, we have used the typology to provide a forward-looking perspective on the development and orientation of the represented niche-innovations (see Table A1 in the supplementary information). High momentum would reflect a change with more immediate effect in the model, whereas lack of momentum, such as considered for most behavioural change niche-innovations (see Figure 2), would result in a delayed effect.

In terms of actual implementation, translation is considered the process of locating the right context variables in the model and setting new values to the default parameterisation (leading to a new model response, as represented in the slope of the lines in Figure 1). These context variables are specific to the model, leaving much of the translation to the interpretation of the modeller. Quantitative findings, such as assumptions about efficiency, can be adopted rather straightforward in a quantitative model. However, if the provided information does not allow to be translated into the mathematical formulations as used in the model (such as the accumulation of knowledge and the reordering of social rules), more stylised methods are employed to impose a change.

Stylised methods that can be implemented are the *linking* or *locking* of dynamical processes in the model. An example of this is the removal of the relative cost differences for specific technologies in a portfolio (e.g. by allowing the higher levelised costs of electricity for offshore wind to converge to the lower levelised costs of electricity for onshore wind over time). This narrative-based assumption would imply an accumulation of interest, leading to faster runs through the innovation cycles than under default assumptions in the model. Alternatively, an example of locking, or changing societal rule-sets, can be considered by not allowing any further growth compared to a certain base year (e.g. no further growth of the household size beyond 40 m^2/cap in urban areas, as a "behavioural change" measure for the heating domain). Abstracting such interventions allows us to adopt a new parameterisation of the models' context variables without underpinning the change with explicit numerical evidence (see also van Sluisveld et al. (2016) for further examples). A full breakdown of specific assumption-based changes to the parameterisation of the TIMER/IMAGE model is presented in table B1 of the supplementary materials.

The narratives have been implemented in an iterative process with the scientists involved with the MLP case-studies, leading to an interactive setting in which a "zero-order" implementation has been discussed and revised (see Turnheim et al. (2015) for a conceptual outline of the process). Some inconsistency may occur with the new parameterisation and the qualitative findings, as qualitative knowledge may not translate completely into a deductible quantitative input. Two deliberate inconsistencies have been adopted in the *Broader Regime Change* transition narrative – including no new construction of nuclear energy from the start of the simulation and no implementation of carbon capture and storage technologies - as these technologies had not been formally classified as niche-innovations.

2.4 Defining transition narratives to a low-carbon Europe

The typology as presented in Figure 2 presents the orientation of niche-innovations under current day considerations and provides only limited information on the implications over time under a changing landscape. Hence, to assess the ramifications of specific social system configurations on the low-carbon strategy, we impose an exogenous pressure to emulate a specific long-term normative (climate) goal. In IAMs this is usually done by introducing pricing policies that shift the balance in the models' decision mechanisms for technology and services deployment. To align the transition narratives to the European goal of reducing domestic reductions by 80% in 2050 compared to 1990 levels, we impose a continuous and increasing system pressure in the form of a carbon price[4]. This carbon price should be seen as a generic policy pressure that leads to systemic behaviour oriented towards a low-carbon transition in line with the EU 2050 objective. The carbon price is harmonised across the two different transition narratives. Table 1 provides an overview of the scenario architecture in this study.

Table 1 – overview of the scenario architecture

Transition narrative	Actor representation	Short name	Origin	Mitigation goal
Historical reference	-	2010	TIMER/IMAGE	-
Techno-economic optimisation	Rational-economic agent	*Default*	SSPs [1]	Global 2°C [2]
Technological substitution	Incumbents	*TechSub*	PATHWAYS[3]	-80% EU 2050
Broader regime change	New actors	*RegChange*	PATHWAYS[3]	-80% EU 2050

[1]For the purpose of this study we build on the new scenario framework for climate change research, also called Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014). We select the middle-of-the-road narrative (SSP2) as the common storyline, representing a future with moderate mitigation and adaptation challenges (in terms of sustainable development, inequalities, technological change, and productivity of land).

[4] The common pricing policy assumed in IAMs is the so-called "carbon price" (or tax) which adds a disadvantage to technologies and services that devise fractions of carbon content within their functional unit. Although often called "carbon tax", this parameter may be interpreted in the widest form of top-down steering, and may therefore just as well represent other policy instruments leading to a cost-optimal implementation of policies.

[2] The mitigation goal here is defined as "Global 2°C" which represents a global commitment to limiting global warming by no more than 2°C in 2100 with respect to the pre-industrial level. In the conclusions of the 4th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), Annex-I (developed) countries were advised to reduce greenhouse gas emissions by 80%-95% in 2050 compared to 1990 levels as to remain aligned with the 2°C global objective (Council of the European Union, 2009; Gupta et al., 2007). As such, a global 2°C objective can be considered compatible with meeting the EU objective in 2050.

[3] These scenarios have been developed as part of the PATHWAYS project, which explored transition pathways to a low-carbon, sustainable Europe under different disciplinary lenses (Geels et al., 2016; Turnheim et al., 2015).

3 Findings on new transition pathways

The effect of specific social actor configurations in adopting low-carbon transition strategies is analysed by comparing the numerical output (also called "pathways" if we consider the development over time) of the TIMER/IMAGE model for both transition narratives to a regular cost-optimal pathway. We particularly look at the *emission* pathways to gain insights into the overall human-climate interaction over time, and the *technology deployment* pathways to gain insights into the changes on the sector and technology level (Rosenbloom, 2017).

3.1 Emission pathways

Achieving the European emission reduction objective demands a clear deviation from current emission levels (see Figure 3). Although GHG emissions are reduced by 80% by 2050 in all three scenarios, they differ in terms of depth and timing of emission reductions. The new transition scenarios both show a faster reduction in GHG emissions than the *Default* pathway, with the *RegChange* scenario showing the fastest reductions. By 2050, the *Default* and *TechSub* scenarios both deploy negative emissions as a prominent strategy for the power sector. The *TechSub* scenario, however, shows to have a lower dependency on negative emissions due to taking note of specific socio-technical tendencies in technological growth and deployment. In the absence of negative emission technologies (*RegChange)*, deeper emission reductions throughout all sectors are needed to remain aligned to the 80% emission reduction target in 2050. Figure 3 also reveals that the main challenge for sectors is on mitigating CO_2 emissions, as non-CO_2 emissions show to be negated more rapidly.

[FIGURE 3 HERE]

Figure 3 –Total greenhouse gas emissions for Europe disaggregated per economic sector, excluding emissions from Land Use, Land Use Change and Forestry (LULUCF). Sectoral emissions show total CO_2 emissions per sector, the sum of non-CO_2 emissions (representing CH_4, N_2O and F-gasses) are depicted separately.

3.2 Technology pathways

In comparing the technology deployment pathways, it is essential to distinguish between the demand and supply of energy. We use the total energy consumption for specific technologies and services (in EJ/yr) as the functional unit to compare across the various services (demand) and technologies (supply). The focus on energy consumption also allows an inter-sectoral comparison of both (1) (fuel) substitution behaviour or demand reduction (as can be deducted in the absolute values) and (2) insights on niche momentum or system inertia (as can be deducted from the relative contribution to the total).

3.2.1 Sector-level changes

A first indication of shifted or maintained systems can be obtained from examining changes in service demand. In the *TechSub* and *Default* scenarios, efficiency gains lead to a lower total energy demand in 2030 than in 2010, with no major difference between these scenarios (see Figure 4). The *RegChange* scenario depicts larger reductions in total energy demand, mainly due to 1) lower household energy consumption as a result of lower space heating demand, and 2) lower energy consumption in transport as a result of reduced passenger air and road travel. Over a longer time horizon, total energy demand decreases further with the largest reductions in the *RegChange* scenario. Interestingly, the *TechSub* and *RegChange* scenarios become less dependent on liquid energy carriers than the *Default* scenario. For the *TechSub* scenario this can be explained by the accelerated electrification of the transport sector, while in the *RegChange* scenario this reduction represents a decline in air travel and an increase in public transport (train). In the *RegChange* scenario gaseous fuels are reduced more strongly than in the other scenarios as a result of a lower demand for space heating.

[FIGURE 4 HERE]

Figure 4 - Total final energy demand for each resource and total demand for transport and residential sector services in Europe.

3.2.2 Technological configurations

Until 2030, both the *TechSub* and *RegChange* scenarios show no substantial differences for the power sector compared to the *Default scenario*. This implies some systemic inertia, which can be attributed to the lifetime of existing capital and the postponement of new investment decisions beyond the 2025-2030 timeframe in the model. Inertia is found to play a smaller role in the transport sector due to the lower capital lifetimes of cars compared to the technologies in the power sector. This becomes particularly visible in the significant change in the composition of the passenger vehicle fleet in the *TechSub* scenario by 2030, both compared to 2010 and to the other scenarios. The *RegChange* scenario does not seem to follow the developments as expected under cost-optimal representations, as total energy demand is much lower due to changes in travel demand and differences in the mode split (presented in Figure 4). For the heating domain, all scenarios depict a dominant and even increasing role for natural gas in space heating in the short term.

Towards 2050, the TIMER/IMAGE model shows a shift to renewable energy technologies, with a preference for onshore wind under *Default* scenario settings. The narrative-based changes seem to affect the merit order, showing an increased preference for offshore wind in the *TechSub*, while a preference for distributed and decentral solutions is seen in the *RegChange* scenario (as reflected in the relative contribution for solar power and onshore wind). Irrespective of having adopted constraints or not, nuclear energy shows to be eventually phased-out in both transition narratives. In the *Default* and *TechSub* scenario, nuclear energy appears to be substituted by fossil and bioenergy-based thermal power supply with coupling to carbon capture and storage (CCS) systems. As this is a more constant power source, it could be devised as spinning reserve to balance shortages in supply from the more intermittent energy sources. The *RegChange* scenario, on the other hand, depends more on intermittent energy technologies, showing only marginal contribution of other technologies (such as bioelectricity and hydro power).

The effects of the transition narratives are also visible for specific demands over time, such as found for private road travel and heating. We find that under the *Default* scenario the (gasoline-based) internal combustion engine (ICE) vehicle is maintained, with only some marginal diversification in the passenger car fleet by 2050. This is in stark contrast with the *TechSub* scenario, in which the battery electric vehicle (BEV) has almost fully overtaken the private vehicle fleet in road travel. The *RegChange* scenario is characterised by major reductions in total energy use for passenger travel as a result of behavioural change. Interestingly, although a scenario without "negative emission" technologies (*RegChange*) would necessitate a greater electrification of energy demand sectors, some dependency remains on gasoline-based vehicles by 2050 (as a result of higher electricity prices). For heating, some rebound effects can be observed in the *TechSub* scenario, given the increase of oil-fired and gas-fired boilers compared to the *Default* scenario, indicating that electrification in some areas leads simultaneously to the strengthening of existing fossil-based regimes elsewhere. Only for the *RegChange* scenario some momentum is depicted for the considered niche-innovations, as "small scale biomass" and the "heat pump" (denoted as ASHP in Figure 5) find some market share. The findings underline that the buildings domain is strongly inert; however, it should also be noted that the TIMER/IMAGE model has only a limited representation of the considered building stock and lacks explicit detail on the technology-level.

[FIGURE 5 HERE]

Figure 5 - Technology change for the power sector, passenger cars and heating technologies in Europe. CCS: carbon capture and storage. BEV: Battery Electric Vehicle. PHEV: Plug-in Hybrid Electric Vehicle. ICE: Internal Combustion Engine. ASHP: Air-source Heat Pump. Boiler|Mod.Bio: (advanced) biofuel-powered boilers/ Bioler|Trad.Bio: Boiler powered on wood pellets.

4 Discussion

In this study we have presented a method for a conceptual interaction between integrated assessment modelling and insights from the multi-level perspective. The conceptual interaction started with formulating qualitative transition narratives. These narratives have been the main vehicle for carrying information on (1) the current momentum of various niche-innovations in three different sectors and (2) the strategic actors driving the change. In a follow-up step the qualitative narratives have been translated into quantitative scenarios that could be implemented into a computational integrated assessment model (TIMER/IMAGE). The narratives thus provide a new logic to the driving forces of the model, with explicit focus on actors, for which modellers have selected appropriate numerical representations. However, as the embedment of social science insights into natural science oriented disciplines has taken the centre stage in this study (as raised in e.g. van Vuuren et al. (2012); Victor (2015)), a more pragmatic approach has been adopted to overcome specific methodological challenges. In the following sections these challenges are addressed to more detail, distinguishing between the narrative development phase and the qualitative-to-quantitative translation processes.

4.1 Narrative development

A first methodological challenge relates to the interpretation of detailed information from MLP assessment. To quantitatively assess the impact of a transition narrative with an IAM model like TIMER/IMAGE requires to (1) draw a uniform direction of change for each scenario and therefore (2) assume scalability and comparability of case-study results within the European resolution of the model. This is a deliberate narrowing of the richness and qualitative detail of the MLP assessments. In that regard, the established operational link is rather deterministic and static in nature, even though it is acknowledged that socio-technical elements are more volatile and may change over time. Scholarly literature has proposed various techniques and methods to develop and study a pluralist approach, or a wider range of narratives, addressing both the diversity and the vulnerability of transition narratives in a more structured and transparent way (see e.g. Guivarch et al. (2017); Trutnevyte et al. (2016); van 't Klooster and van Asselt (2006); Wright et al. (2013)). Future work could ideally focus on expanding the current methodology to concepts that account for divergent views. This would benefit the conceptual interaction between the analytical fields while leading to a better understanding of long-term transitions and the role of actors in driving the change.

A second methodological challenge relates to the prevailing techno-economic focus in narrating low-carbon transitions. This techno-economic orientation may be a result of "availability" biases in both analytical approaches, which impose restrictions to how transitions and responses are explained in the current results. On the one hand, the selection of case-studies shows a preference for (1) technological substitution niche-innovations, (2) small-scale innovations over more large-scale system changes, and (3) existing concepts rather than new and disruptive innovations. Conversely, IAMs mostly connect to technologies and processes that are very thoroughly or explicitly modelled, particularly focusing on elements with a proven experience base (such as large-scale, centralised, technologies). Hence, as *broader regime changes* are not explicitly nor quantitatively represented in the observational data or modelling, many questions relating to the (1) steering of socio-technical potential, (2) representations of new systems, and (3) negating the climatic response in the absence of "negative emission" technologies largely unresolved. How social niche-innovations could be represented in more detail would therefore need further methodological development.

4.2 From qualitative-to-quantitative scenarios

Specific literature exists on the translation of rich qualitative information of non-linear behaviour into applicable inputs for computational models (see Mallampalli et al. (2016) for an overview). However, despite the available knowledge base, the conversion and reproducibility of information remains the weakest link in such translation processes (Alcamo, 2008) for which no definitive solution exists. In this study we demonstrated a more pragmatic approach to bridging analytical differences by defining several operational links. Although it has created new avenues for interaction between two research communities, it is of importance to prolong the engagement with social sciences to build further experience in translating transition narratives to computational models (Brown et al., 2015).

Furthermore, the current study restricts the analysis to only one transition narrative and one model assessment. Adopting also a more pluralistic approach in integrative assessment could broaden the knowledge on long-term development in line with the European climate objective. Particularly multi-model studies are commonly used to examine the effect of epistemic differences in understanding systemic change. However, given differences in the technological, spatial and actor-related resolutions across the range of applicable computational models, this creates difficulties in harmonising the translation process of qualitative transition narratives to comparable quantitative integrative assessment studies (see e.g. Hof et al. (this issue), for a multi-model demonstration). Further methodological development on how to harmonise detailed narrative-driven storylines would reap benefits for long-term transition narrative assessments in the future.

5 Conclusions

Integrated Assessment Models of global change (IAMs) contain a wealth of information on the interrelations and feedbacks between natural and human systems. However, devising aggregated formulations of systems change in mathematical formulations and projecting these developments into the future leaves room for debate on the representation of (1) actual system change and (2) the drivers of systems changes. Earlier work has focussed on improving (modelling) or framing (scenario narratives) the course of systemic change under carbon constraints, though remained evasive of explicitly addressing factors that shape change within society. This study has been motivated by the assumption that qualitative insights from socio-technical transition studies (MLP) can help inform model-based analysis (IAM) on the actors and processes driving change while explicitly accounting for their effect on current systems and regimes. By operationalising conceptual interaction between MLP and IAM, we have introduced a new analytical method to bridge the gap in qualitative and quantitative assessment of low-carbon transitions and propagated a new way to study and include more realistic emerging trends in futures studies. The study allows us to draw the following lessons:

MLP can function as a useful heuristic for IAMs to analyse new and emerging directions of change

By systematically and consistently assessing a variety of niche-innovations across a range of European countries with MLP, it provided a (1) snapshot of the current momentum in a wide range of niche-innovations and (2) a classification of the strategic actors mobilising a prospective transition (limited to incumbents and new actors). The results have powered two fundamentally different transition narrative scenarios with respect to the role of actors, the role of governance and the kind of technologies being considered, whose impact to long-term future system change could be assessed with the TIMER/IMAGE model. The resulting transition narratives specifically allowed for a gradual and mixed implementation of impulses reflective of actual change in otherwise rather stylised representations of change in model-based scenarios. Although the conceptual interaction between MLP and IAM has strengthened the general understanding of systems change, several methodological challenges have been left unresolved. Hence, future research could focus on the further joining of methodologies to explore the effect of social actors in driving future low-carbon change.

Different pathways are compatible with meeting the 80% emission reduction target in Europe by 2050

The modelling exercise revealed that different transition pathways could meet the European GHG emission reduction objective by 2050. In the rationale of the considered transition narratives and as part of the mechanics of the TIMER/IMAGE model, this resulted into an explorative exercise on how a long-term objective could be met in the presence or absence of “negative emission” technologies. In the presence of such technologies, the transition scenario framed around technological substitution methods, resulting in a more rapid decarbonisation of the power supply sector and reducing carbon emissions via carbon removal and storage technologies. In the absence of such technologies, intermittent renewable energy technologies and demand reductions are notably more important to remain aligned with the European GHG emission reduction objective. Despite an assumed low momentum for behavioural change niche-innovations in the present, the effect of demand-oriented solutions on reducing emissions is considered significant for those sectors and services that are in close proximity to the user (respectively heating and transport). In both transition scenarios, additional system pressure has been imposed to align current systems to global climate objectives. Public policies are therefore important to drive either a more rapid technological transition (technology substitution) or to ensure that new actors can play a more important role (broader regime shift).

Greater focus needed on demand-oriented solutions in techno-economic assessment

Although the transition narratives have changed the responses of the TIMER/IMAGE model, most of the demand-oriented solutions find implementation via ad-hoc and assumption-based changes. As such, transition narratives that are dependent on more socio-cognitive changes or overall broader regime change may find only limited representation in techno-economic assessment. This leaves many questions relating to future (1) steering of socio-technical potential, (2) representations of new systems, and (3) negating the climatic response in the absence of "negative emission" technologies largely unanswered. These limitations should be devised as encouragement to pursue further development in this direction.

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